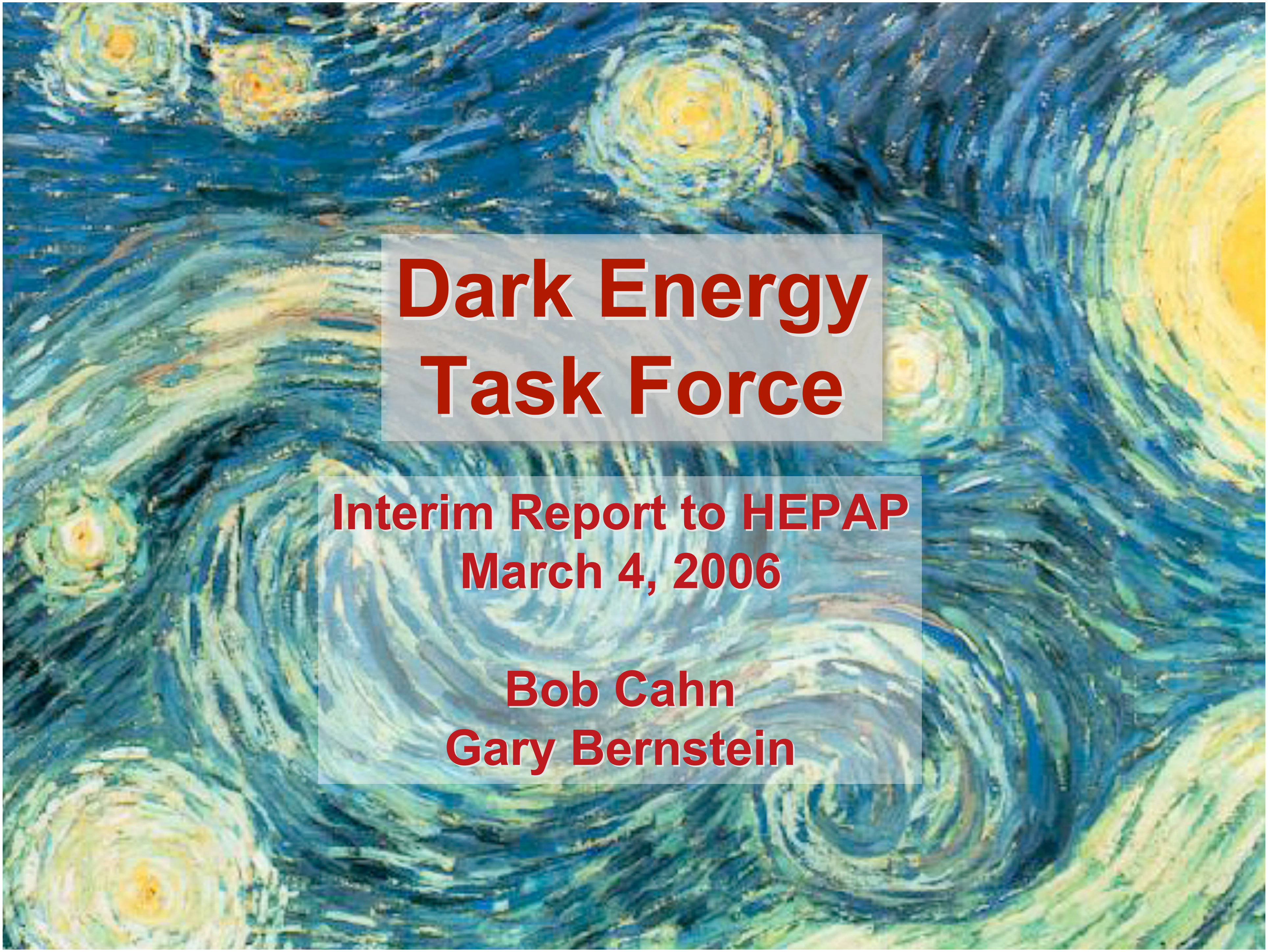

Dark Energy Task Force

Interim Report to HEPAP
March 4, 2006

Bob Cahn
Gary Bernstein

Dark Energy Task Force (DETF)

http://www.nsf.gov/mps/ast/detf.jsp

• Three agencies:	DOE; NASA; NSF
• Two subcommittees:	AAAC (Illingworth); HEPAP (Shochet)
• Two charge letters:	Kinney (NASA); Staffin (DOE); Turner (NSF)
• Twelve members:	Overlap with AAAC, HEPAP, SDT
• One chair:	Rocky Kolb (Fermilab/Chicago)

DETF Membership

- Members
  Andy Albrecht, Davis
  Gary Bernstein, Penn
  Bob Cahn, LBNL
  Wendy Freedman, OCIW
  Jackie Hewitt, MIT
  Wayne Hu, Chicago
  John Huth, Harvard
  Mark Kamionkowski, Caltech
  Rocky Kolb, Fermilab/Chicago
  Lloyd Knox, Davis
  John Mather, GSFC
  Suzanne Staggs, Princeton
  Nick Suntzeff, NOAO

- Agency Representatives
  - DOE: Kathy Turner
  - NASA: Michael Salamon
  - NSF: Dana Lehr

Dark Energy Task Force (DETF)

http://www.nsf.gov/mps/ast/detf.jsp

• Face Meetings:	March 22–23, 2005	@ NSF
	June 30–July1, 2005	@ Fermilab
	October 19–21, 2005	@ Davis
	December 7–8, 2005	@ MIT

• Friday phonecons

• More than 10^3 email messages

• Fifty "White Papers" solicited from Community

Dark Energy Task Force Charge*

"The DETF is asked to advise the agencies on the optimum† near and intermediate-term programs to investigate dark energy and, in cooperation with agency efforts, to advance the justification, specification and optimization of LST and JDEM."

1. Summarize existing program of funded projects
2. Summarize proposed and emergent approaches
3. Identify important steps, precursors, R&D, …
4. Identify areas of dark energy parameter space existing or proposed projects fail to address
5. Prioritize approaches (not projects)

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* Fair range of interpretations of charge.

† Optimum ≡ minimum (agencies); Optimum ≡ maximal (community)

Dark Energy Task Force Report

I. Context:

- The issue: acceleration of the Universe
- Possibilities: dark energy (Λ or not), non-GR
- Motivation for future investigations

II. Goals and Methodology:

- Goal of dark energy investigations
- Methodology to analyze techniques/implementations

III. Findings:

- Techniques (largely from White Papers)
- Implementations (largely from White Papers)
- Systematic uncertainties
- What we learned from analysis

IV. Recommendations: (not yet ready for prime time)

V. Technical appendices

Context

1. Conclusive evidence for acceleration of the Universe.
   Standard cosmological framework → dark energy (70% of mass-energy).
2. Possibility: Dark Energy constant in space & time (Einstein's Λ).
3. Possibility: Dark Energy varies with time (or redshift z or $a = (1+z)^{-1}$).
4. Impact of dark energy can be expressed in terms of "equation of state" $w(a) = p(a) / \rho(a)$ with $w(a) = -1$ for Λ.
5. Possibility: GR or standard cosmological model incorrect.
6. Whatever the possibility, exploration of the acceleration of the Universe will profoundly change our understanding of the composition and nature of the Universe.

Context

7. Dark energy appears to be the dominant component of the physical Universe, yet there is no persuasive theoretical explanation. The acceleration of the Universe is, along with dark matter, the observed phenomenon which most directly demonstrates that our fundamental theories of particles and gravity are either incorrect or incomplete. Most experts believe that nothing short of a revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration. For these reasons, the nature of dark energy ranks among the very most compelling of all outstanding problems in physical science. These circumstances demand an ambitious observational program to determine the dark energy properties as well as possible.

Goals and Methodology

1. The goal of dark-energy science is to determine the very nature of the dark energy that causes the Universe to accelerate and seems to comprise most of the mass-energy of the Universe.
2. Toward this goal, our observational program must:
   a. Determine as well as possible whether the accelerated expansion is consistent with being due to a cosmological constant.
   b. If it is not due to a constant, probe the underlying dynamics by measuring as well as possible the time evolution of dark energy, for example by measuring $w(a)$; our parameterization is $w(a) = w_0 + w_a(1 - a)$
   c. Search for a possible failure of GR through comparison of cosmic expansion with growth of structure.
3. Goals of dark-energy observational program through measurement of expansion history of Universe [$d_L(z)$, $d_A(z)$, $V(z)$], and through measurement of growth rate of structure. All described by $w(a)$. If failure of GR, possible difference in $w(a)$ inferred from different types of data.

Goals and Methodology

4. To quantify progress in measuring properties of dark energy we define dark energy figure-of-merit from combination of uncertainties in w_0 and w_a. (Caveat.)
5. We made extensive use of statistical (Fisher-matrix) techniques incorporating CMB and H_0 information to predict future performance (75 models).
6. Our considerations follow developments in Stages:
   I. What is known now (12/31/05).
   II. Anticipated state upon completion of ongoing projects.
   III. Near-term, medium-cost, currently proposed projects.
   IV. Large-Survey Telescope (LST) and/or Square Kilometer Array (SKA), and/or Joint Dark Energy (Space) Mission (JDEM).
7. Dark-energy science has far-reaching implications for other fields of physics → discoveries in other fields may point the way to understanding nature of dark energy (*e.g.,* evidence for modification of GR).

Astronomy Primer for Dark Energy

Solve GR for the scale factor *a* of the Universe (*a*=1 today):

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

Positive acceleration clearly requires $w = P/\rho < -1/3$, unlike any known constituent of the Universe, or a non-zero cosmological constant - or an alteration to General Relativity.

The second basic equation is $$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho}{3} + \frac{\Lambda}{3} - \frac{k}{a^2}$$

Today we have $$H_0^2 = \frac{8\pi G_N \rho_0}{3} + \frac{\Lambda}{3} - k$$

Hubble Parameter

We can rewrite this as

$$1 = \frac{8\pi G_N \rho_0}{3H_0^2} + \frac{\Lambda}{3H_0^2} - \frac{k}{H_0^2} \equiv \Omega_\rho + \Omega_\Lambda + \Omega_k$$

To get the generalization that applies not just now (a=1), we need to distinguish between non-relativistic matter and relativistic matter. We also generalize Λ to dark energy with a constant *w*, not necessarily equal to -1:

non-rel. matter **curvature**

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right]$$

rel. matter **Dark Energy**

What are the observable quantities?

Expansion factor *a* is directly observed by redshifting of emitted photons: *a=1/(1+z)*, *z* is “redshift.”

Time is *not* a direct observable (for present discussion). A measure of elapsed time is the *distance* traversed by an emitted photon:

$$0 = ds^2 = c^2 dt^2 - a^2(t)[dr^2 + r_0^2 S_k^2(r/r_0) d^2\Omega] \quad \Rightarrow$$

$$D(z) = \int_{t(z)}^{t_0} \frac{c\,dt'}{a(t')} = \int_0^z \frac{c\,dz'}{H(z')}$$

This ***distance-redshift relation*** is one of the diagnostics of dark energy. Given a value for curvature, there is 1-1 map between *D(z)* and *w(a).*

Distance is manifested by changes in flux, subtended angle, and sky densities of objects at fixed luminosity, proper size, and space density. These are one class of observable quantities for dark-energy study.

Another observable quantity:

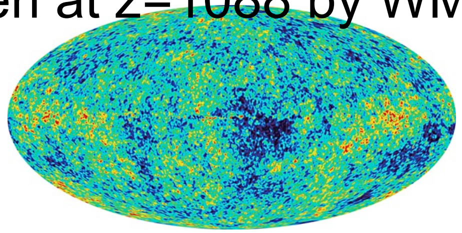
The progress of gravitational collapse is damped by expansion of the Universe. Density fluctuations arising from inflation-era quantum fluctuations increase their amplitude with time. Quantify this by the ***growth factor g*** of density fluctuations in linear perturbation theory. GR gives:

$$\ddot{g} - 2H\dot{g} = 4\pi G\rho_m g = \frac{3\Omega_m H_0^2}{2a^3} g$$

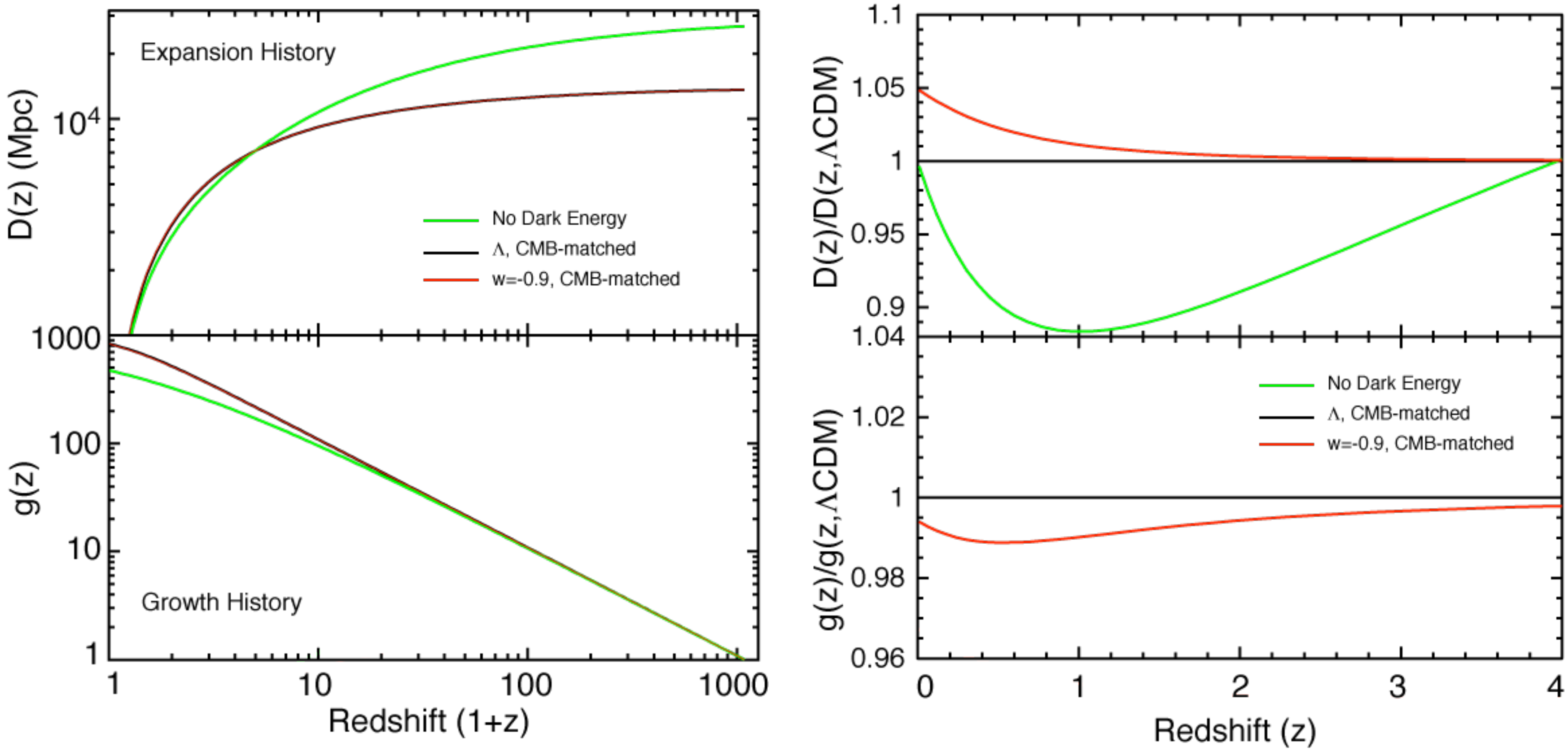
This ***growth-redshift relation*** is the second diagnostic of dark energy. If GR is correct, there is 1-1 map between *D(z)* and *g(z).*

If GR is incorrect, observed quantities may fail to obey this relation.

Growth factor is determined by measuring the density fluctuations in nearby dark matter (!), comparing to those seen at z=1088 by WMAP.



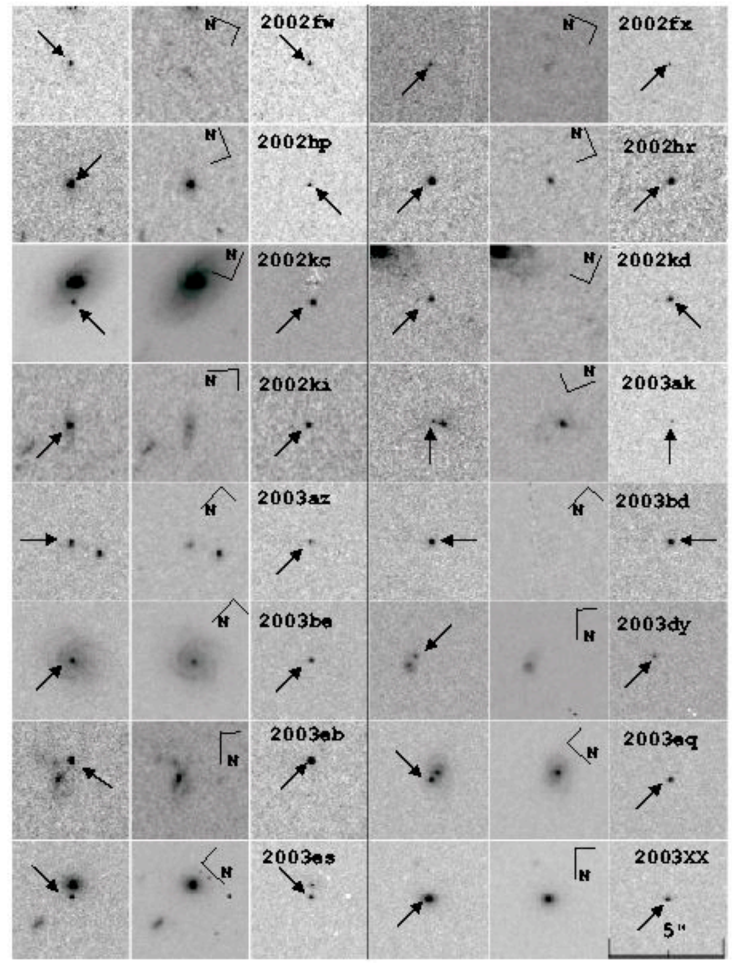
What are the observable quantities?



Future dark-energy experiments will require percent-level precision on the primary observables D(z) and g(z).

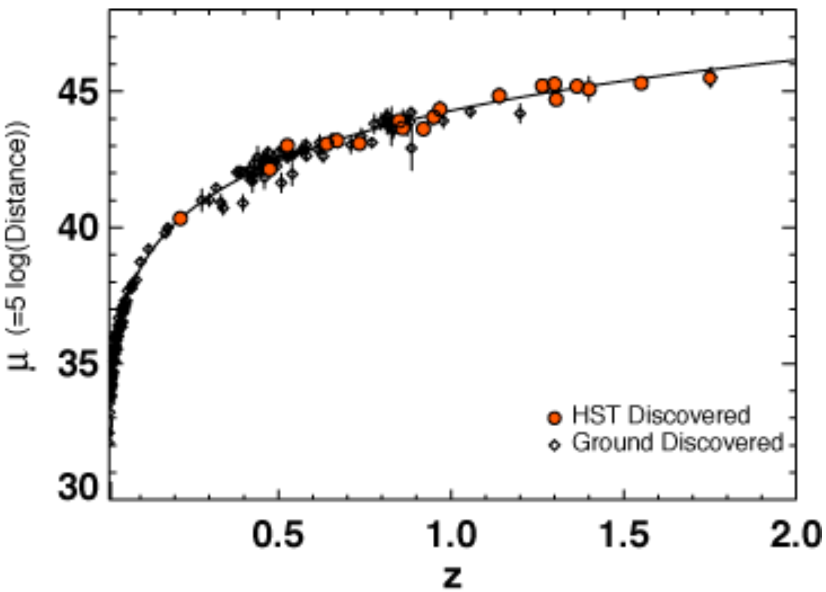
Dark Energy with Type Ia Supernovae

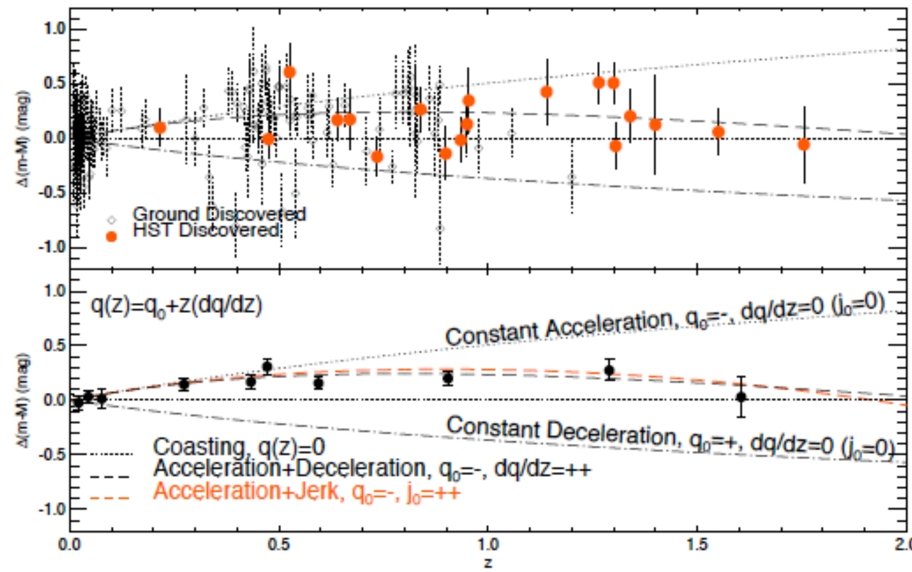
- Exploding white dwarf stars: mass exceeds Chandrasekhar limit.
- If luminosity is fixed, received flux gives relative distance via $f=L/4\pi D^2$.
- SNIa are *not* homogeneous events. Are all luminosity-affecting variables manifested in observed properties of the explosion (light curves, spectra)?

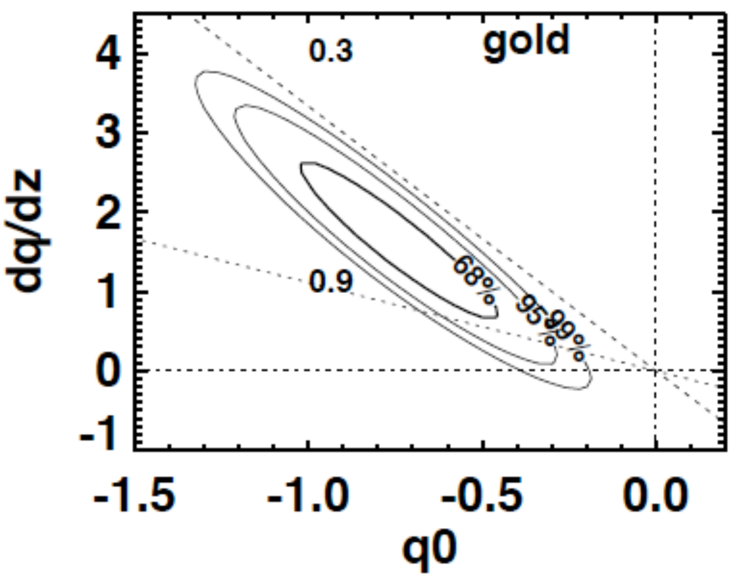


Supernovae Detected in HST GOODS Survey (Riess et al)

Dark Energy with Type Ia Supernovae







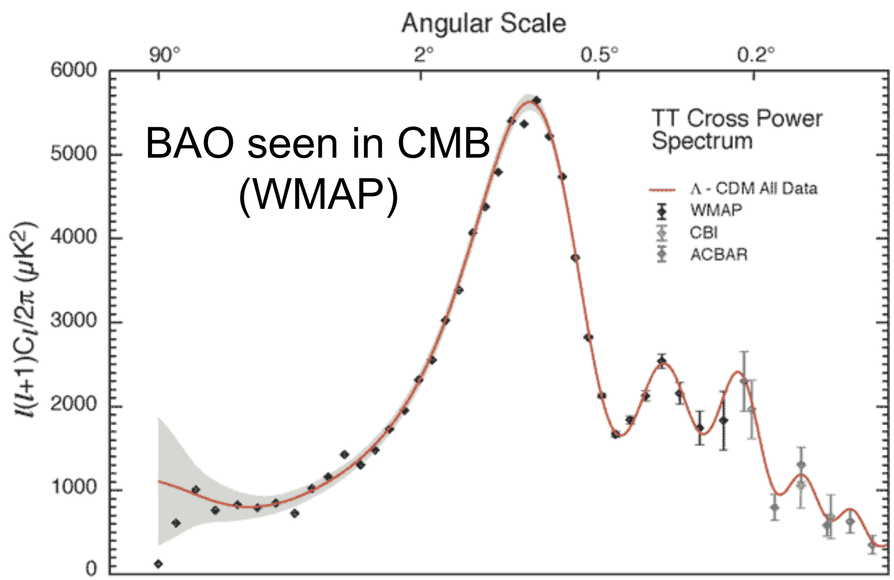
Example of SN data:
HST GOODS Survey (Riess et al)

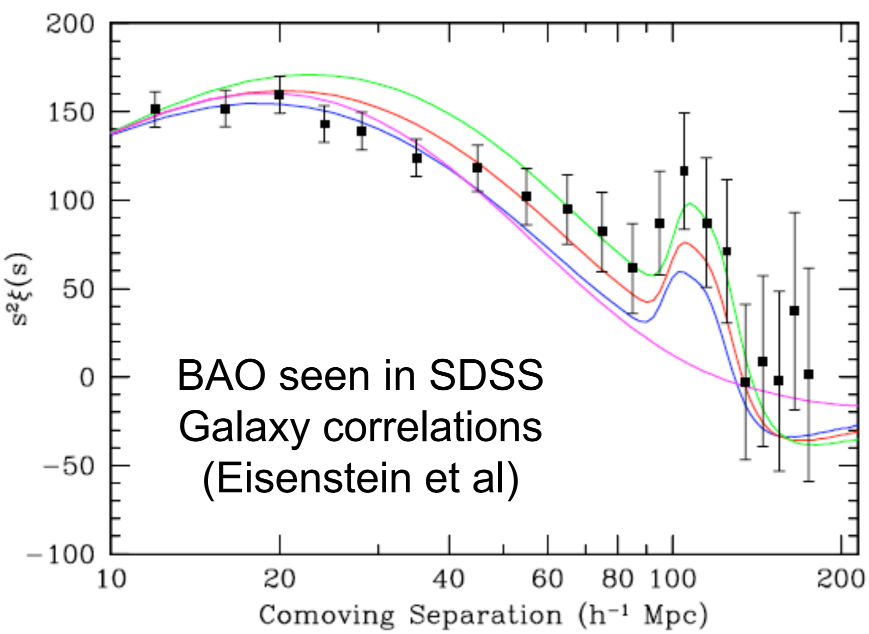
Clear evidence of acceleration!

$$q_0 \equiv -\frac{\ddot{a}_0 a_0}{\dot{a}_0^2} = \frac{1}{2}\left[\Omega_m + \Omega_X(1+3w)\right]$$

Dark Energy with Baryon Acoustic Oscillations

- Acoustic waves propagate in the baryon-photon plasma starting at end of inflation.
- When plasma combines to neutral hydrogen, sound propagation ends.
- Total travel distance = *sound horizon* r_s~140 Mpc is imprinted on the matter density pattern.
- Identify the angular scale subtending r_s then use $\theta_s = r_s / D(z)$
- WMAP/Planck determine r_s and the distance to z=1088.
- Survey of galaxies (as signposts for dark matter) recover D(z), H(z) at 0<z<5.
- Galaxy survey can be visible/NIR or 21-cm emission





Dark Energy with Galaxy Clusters

•Galaxy clusters are the largest structures in Universe to undergo gravitational collapse.

•Markers for locations with density contrast above a critical value.

•Theory predicts the *mass function dN/dMdV.* We observe *dN/dzdΩ.*

•Dark energy sensitivity:

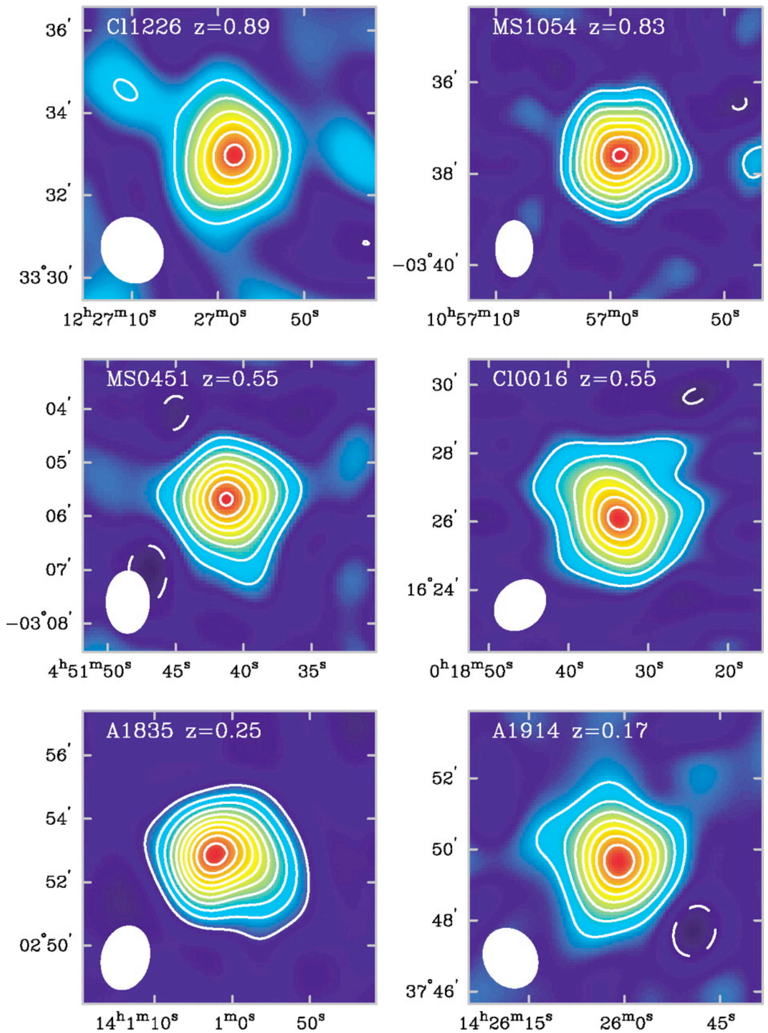
$$dV/d\Omega\, dz \propto D^2(z) H(z)$$

•Mass function is very sensitive to M; very sensitive to g(z).

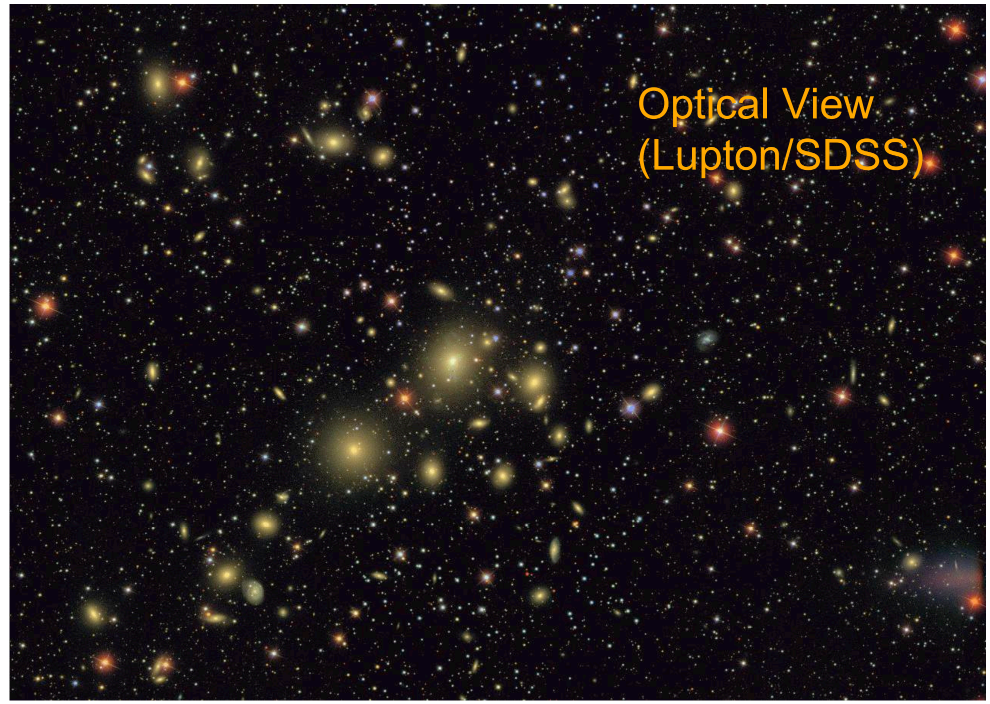
•Also very sensitive to mis-estimation of mass, which is not directly observed.

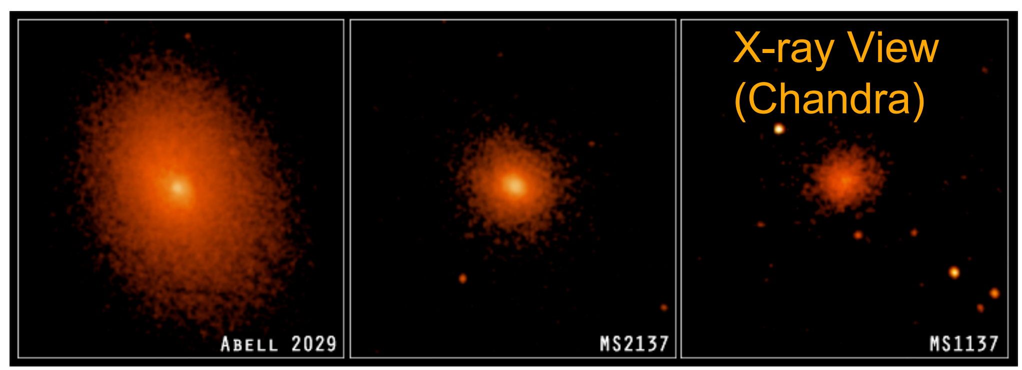
Cluster method probes both D(z) and g(z)

Dark Energy with Galaxy Clusters



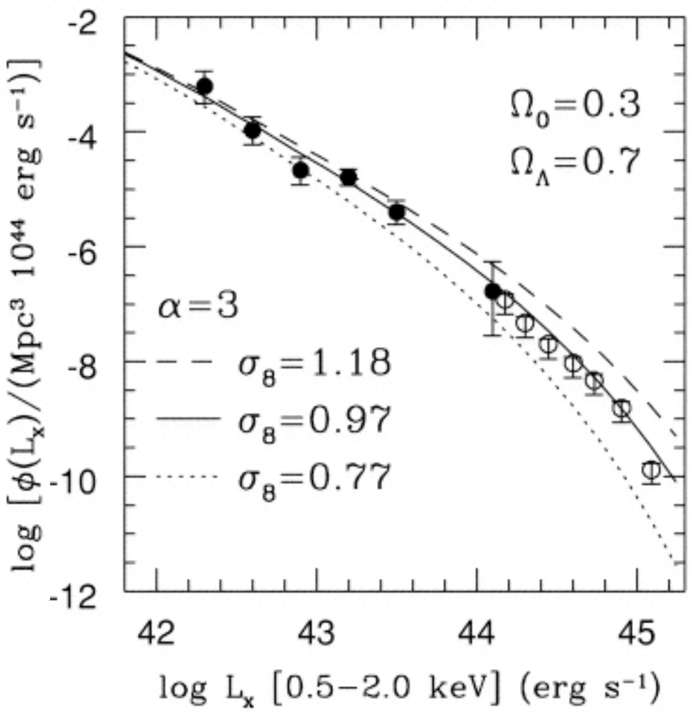
30 GHz View
(Carlstrom et al)
Sunyaev-Zeldovich effect

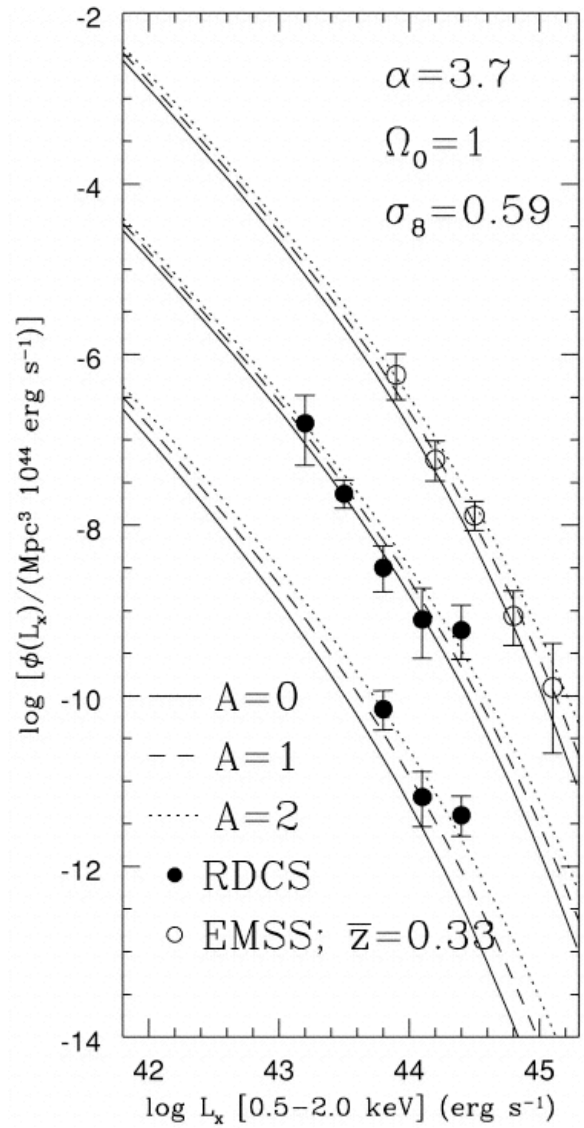




Galaxy Clusters from ROSAT X-ray surveys

From Rosati et al, 1999:





ROSAT cluster surveys yielded ~few 100 clusters in controlled samples.

Future X-ray, SZ, lensing surveys project few x 10,000 detections.

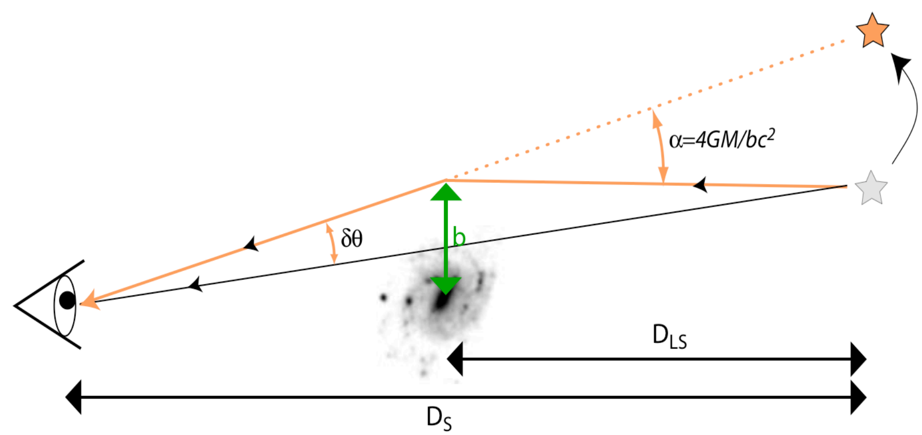
Dark Energy with Weak Gravitational Lensing

•Mass concentrations in the Universe deflect photons from distant sources.

•Displacement of background images is unobservable, but their distortion (shear) is measurable.

•Extent of distortion depends upon size of mass concentrations and relative distances.

•Depth information from redshifts. Obtaining 10^8 redshifts from optical spectroscopy is infeasible. "photometric" redshifts instead.



$$\delta\theta = \frac{4GM}{bc^2}\,\frac{D_{LS}}{D_S}$$

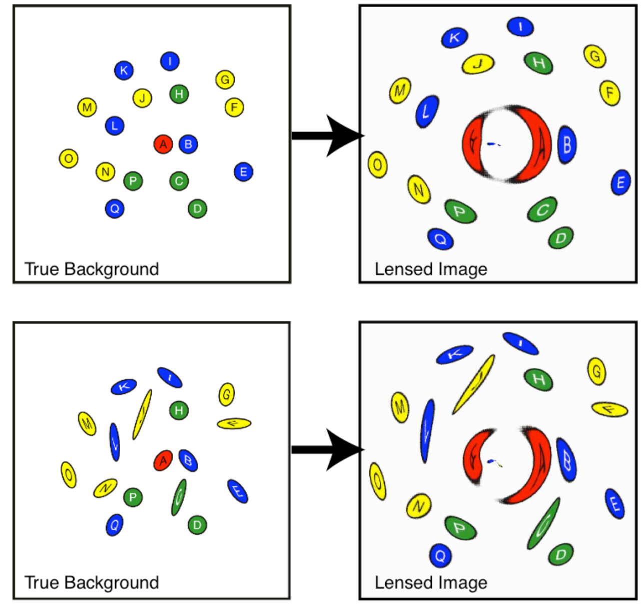
We observe this deflection angle (more precisely, gradients of the deflection angle).

Cosmology changes growth rate of mass structures in the Universe.

Cosmology changes the geometric distance factors.

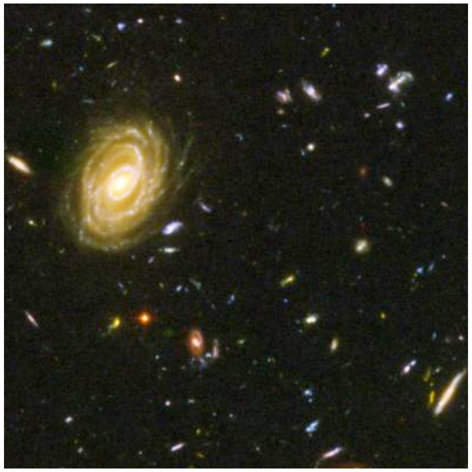
Lensing method probes both D(z) and g(z)

Dark Energy with Weak Gravitational Lensing



In **weak lensing**, shapes of galaxies are measured. Dominant noise source is the (random) intrinsic shape of galaxies. Large-N statistics extract lensing influence from intrinsic noise.

Choose your background photon source:

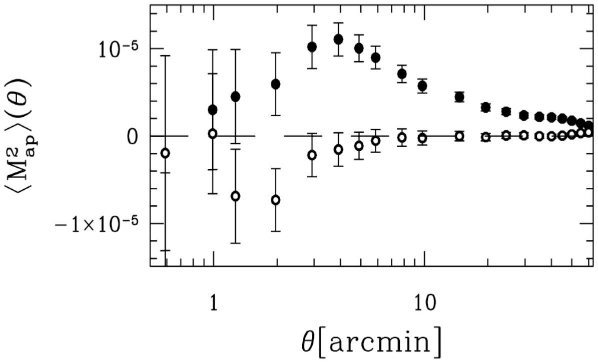


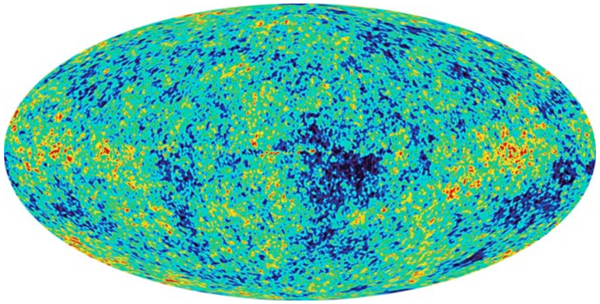
Faint background galaxies:

Use visible/NIR imaging to determine shapes.

Photometric redshifts.

Hoekstra et al 2006:





Photons from the CMB:

Use mm-wave high-resolution imaging of CMB.

All sources at z=1088.

(lensing not yet detected)

21-cm photons:

Use the proposed Square Kilometer Array (SKA).

Sources are neutral H in regular galaxies at z<2, or the neutral Universe at z>6.

(lensing not yet detected)

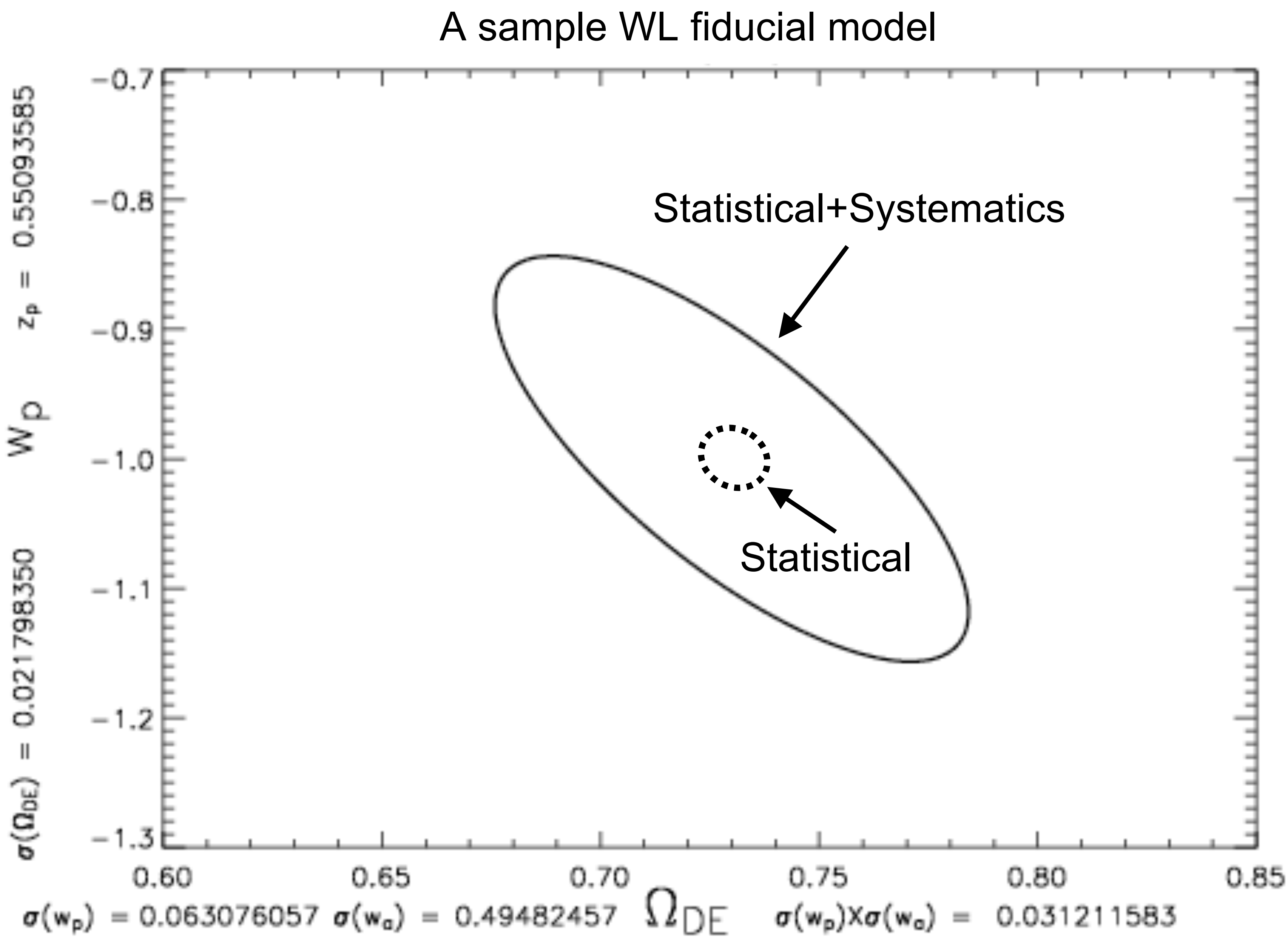
Fifteen Findings

1. Four observational techniques dominate White Papers:
   a. Baryon Acoustic Oscillations (**BAO**) large-scale surveys measure features in distribution of galaxies. BAO: $d_A(z)$ and $H(z)$.
   b. Cluster (**CL**) surveys measure spatial distribution of galaxy clusters. CL: $d_A(z)$, $H(z)$, growth of structure.
   c. Supernovae (**SN**) surveys measure flux and redshift of Type Ia SNe. SN: $d_L(z)$.
   d. Weak Lensing (**WL**) surveys measure distortion of background images due to garavitational lensing. WL: $d_A(z)$, growth of structure.
2. Different techniques have different strengths and weaknesses and sensitive in different ways to dark energy and other cosmo. parameters.
3. Each of the four techniques can be pursued by multiple observational approaches (radio, visible, NIR, x-ray observations), and a single experiment can study dark energy with multiple techniques. Not all missions necessarily cover all techniques; in principle different combinations of projects can accomplish the same overall goals.

Fifteen Findings

4. Four techniques at different levels of maturity:
   a. **BAO** only recently established. Less affected by astrophysical uncertainties than other techniques.
   b. **CL** least developed. Eventual accuracy very difficult to predict. Application to the study of dark energy would have to be built upon a strong case that systematics due to non-linear astrophysical processes are under control.
   c. **SN** presently most powerful and best proven technique. If photo-z's are used, the power of the supernova technique depends critically on accuracy achieved for photo-z's. If spectroscopically measured redshifts are used, the power as reflected in the figure-of-merit is much better known, with the outcome depending on the ultimate systematic uncertainties.
   d. **WL** also emerging technique. Eventual accuracy will be limited by systematic errors that are difficult to predict. *If* the systematic errors are at or below the level proposed by the proponents, it is likely to be the most powerful individual technique and also the most powerful component in a multi-technique program.

Systematics, Systematics, Systematics



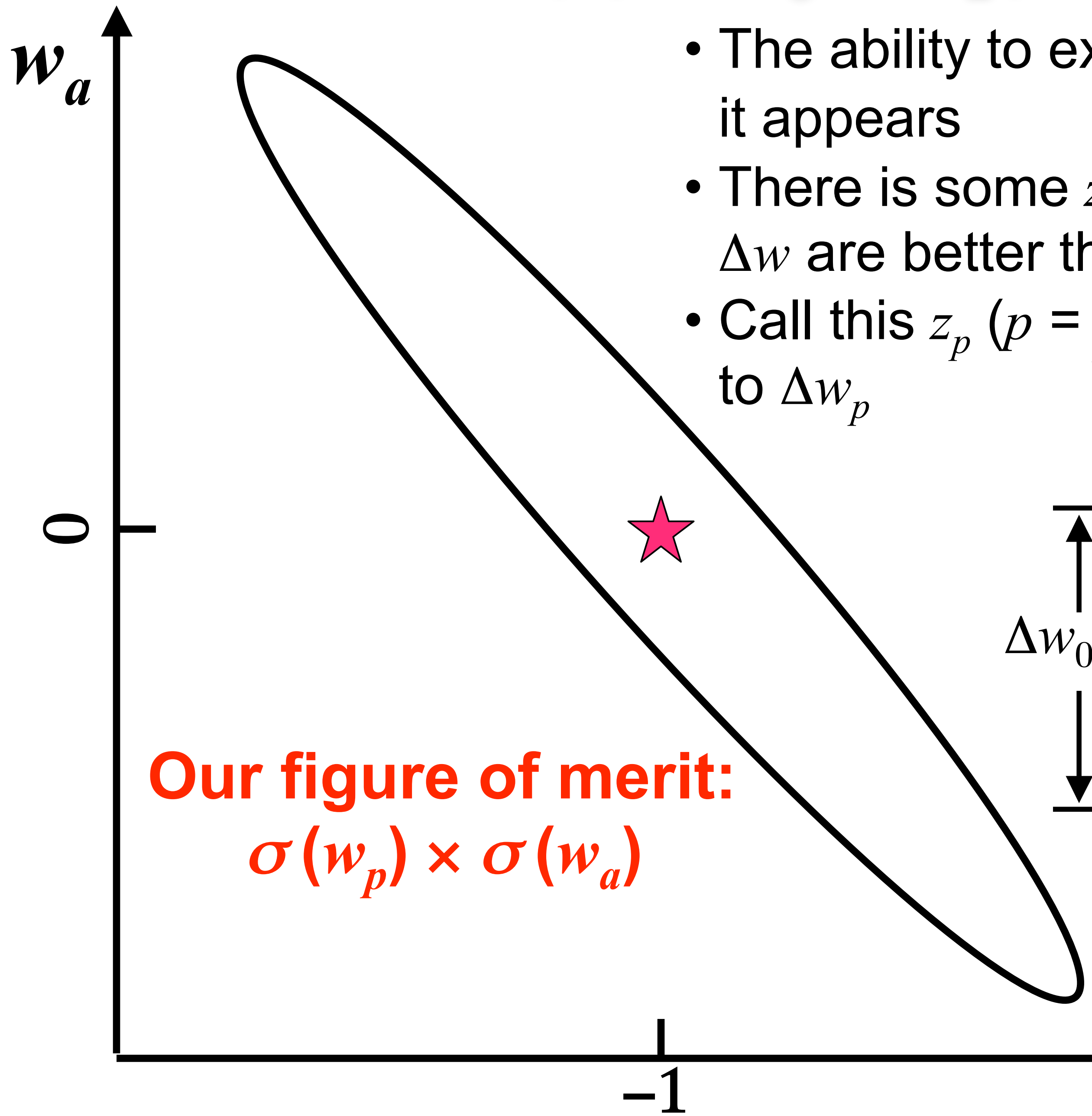
Fifteen Findings

5. A program that includes multiple techniques at Stage IV can provide an order-of-magnitude increase in our figure-of-merit. This would be a major advance in our understanding of dark energy.

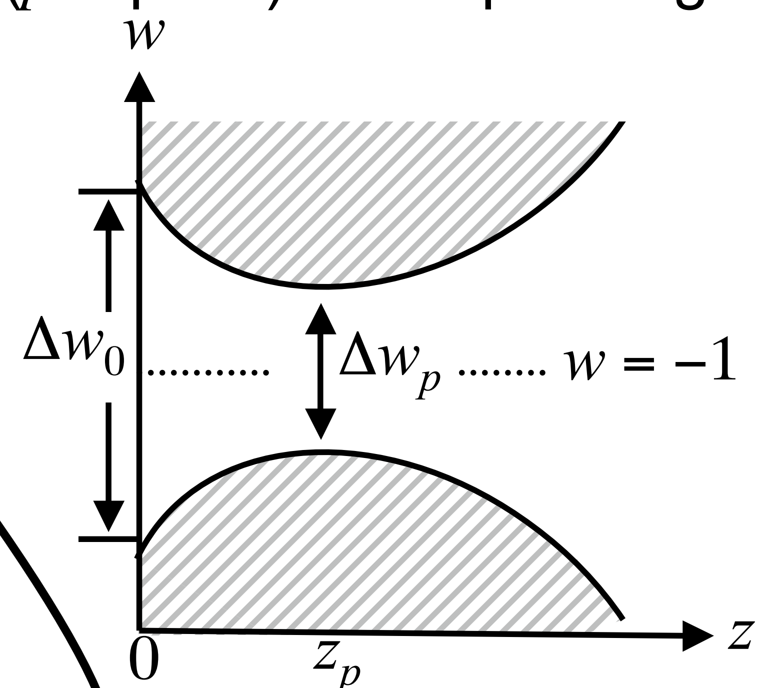
6. No single technique is sufficiently powerful and well established that it is guaranteed to address the order-of-magnitude increase in our figure-of-merit alone. Combinations of the principal techniques have substantially more statistical power, much more ability to discriminate among dark energy models, and more robustness to systematic errors than any single technique. Also, the case for multiple techniques is supported by the critical need for confirmation of results from any single method.

$w(a) = w_0 + w_a(1-a)$

- The ability to exclude Λ is better than it appears
- There is some z where limits on Δw are better than limits on Δw_0
- Call this z_p (p = pivot) corresponding to Δw_p

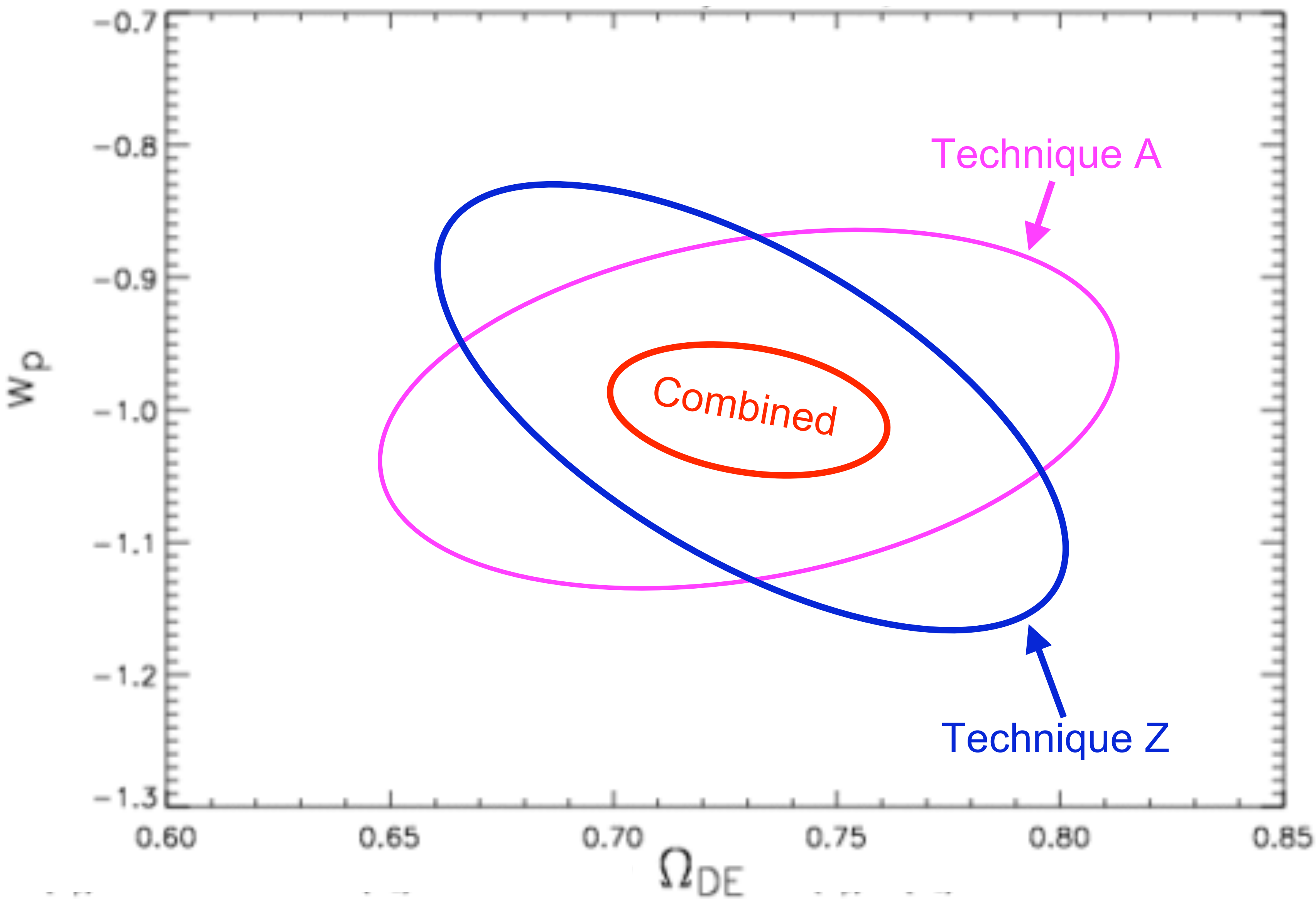


Our figure of merit:
$\sigma(w_p) \times \sigma(w_a)$



The Power of Two (or Three, or Four)

$\sigma(w_p) \times \sigma(w_a) = 0.04$ $\sigma(w_p) \times \sigma(w_a) = 0.009$ $\sigma(w_p) \times \sigma(w_a) = 0.05$



Fifteen Findings

7. Results on structure growth, obtainable from weak lensing or cluster observations, are essential program components in order to check for a possible failure of general relativity.

Fifteen Findings

8. In our modeling we assume constraints on H_0 from current data and constraints on other cosmological parameters expected to come from measurement of CMB temperature and polarization anisotropies.
   a. These data, though insensitive to $w(a)$ on their own, contribute to our knowledge of $w(a)$ when combined with any of the dark energy techniques we have considered.
   b. Different techniques most sensitive to different cosmo. parameters.
   c. Increased precision in a particular cosmological parameter may benefit one or more techniques. Increased precision in a single technique is valuable for the important procedure of comparing dark energy results from different techniques.
   d. Since different techniques have different dependences on cosmological parameters, increased precision in a particular cosmological parameter tends to not improve the figure-of-merit from a multi-technique program significantly. Indeed, a multi-technique program would itself provide powerful new constraints on cosmological parameters.

Fifteen Findings

9. In our modeling we do not assume a spatially flat Universe. Setting the spatial curvature of the Universe to zero greatly helps the SN technique, but has little impact on the other techniques. When combining techniques, setting the spatial curvature of the Universe to zero makes little difference because the curvature is one of the parameters well determined by a multi-technique approach.
10. Experiments with very large number of objects will rely on photometrically determined redshifts. The ultimate precision that can be attained for photo-z's is likely to determine the power of such measurements.

Fifteen Findings

11. Our inability to forecast reliably systematic error levels is the biggest impediment to judging the future capabilities of the techniques. We need
    a. **BAO–** Theoretical investigations of how far into the non-linear regime the data can be modeled with sufficient reliability and further understanding of galaxy bias on the galaxy power spectrum.
    b. **CL–** Combined lensing and Sunyaev-Zeldovich and/or X-ray observations of large numbers of galaxy clusters to constrain the relationship between galaxy cluster mass and observables.
    c. **SN–** Detailed spectroscopic and photometric observations of about 500 nearby supernovae to study the variety of peak explosion magnitudes and any associated observational signatures of effects of evolution, metallicity, or reddening, as well as improvements in the system of photometric calibrations.
    d. **WL–** Spectroscopic observations and narrow-band imaging of tens to hundreds of thousands of galaxies out to high redshifts and faint magnitudes in order to calibrate the photometric redshift technique and understand its limitations. It is also necessary to establish how well corrections can be made for the intrinsic shapes and alignments of galaxies, removal of the effects of optics (and from the ground) the atmosphere and to characterize the anisotropies in the point-spread function.

Fifteen Findings

12. Four types of next-generation (Stage IV) projects have been considered:
    a. an optical Large Survey Telescope (LST), using one or more of the four techniques
    b. an optical/NIR JDEM satellite, using one or more of four techniques
    c. an x-ray JDEM satellite, which would study dark energy by the cluster technique
    d. a Square Kilometer Array, which could probe dark energy by weak lensing and/or the BAO technique through a hemisphere-scale survey of 21-cm emission

    Each of these projects is in the $0.3-1B range, but dark energy is not the only (in some cases not even the primary) science that would be done by these projects.
13. Each of the Stage IV projects considered (LST, JDEM, and SKA) offers compelling potential for advancing our knowledge of dark energy as part of a multi-technique program. According to the White Papers received by the Task Force, the technical capabilities needed to execute LST and JDEM are largely in hand. The Task Force is not constituted to undertake a study of the technical issues.

Fifteen Findings

14. The Stage IV experiments have different risk profiles:
    a. SKA would likely have very low systematic errors, but needs technical advances to reduce its cost. The performance of SKA would depend on the number of galaxies it could detect, which is uncertain.
    b. Optical/NIR JDEM can mitigate systematics because it will likely obtain a wider spectrum of diagnostic data for SN, CL, and WL than possible from ground, incurring the usual risks of a space mission.
    c. LST would have higher systematic-error risk, but can in many respects match the statistical power of JDEM if systematic errors, especially those due to photo-z measurements, are small. An LST Stage IV program can be effective only if photo-z uncertainties on very large samples of galaxies can be made smaller than what has been achieved to date.
15. A mix of techniques is essential for a fully effective Stage IV program. No unique mix of techniques is optimal (aside from doing them all), but the absence of weak lensing would be the most damaging provided this technique proves as effective as projections suggest.